Common energy scale for magnetism and superconductivity in the cuprates.

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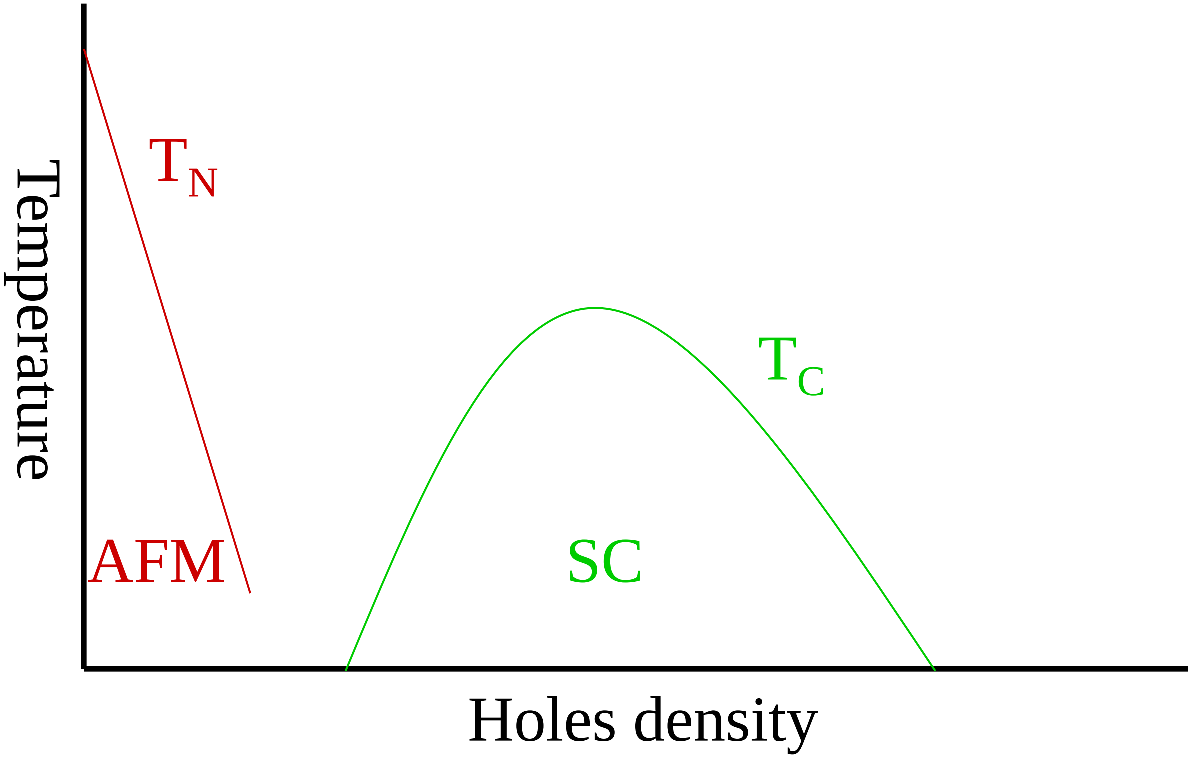
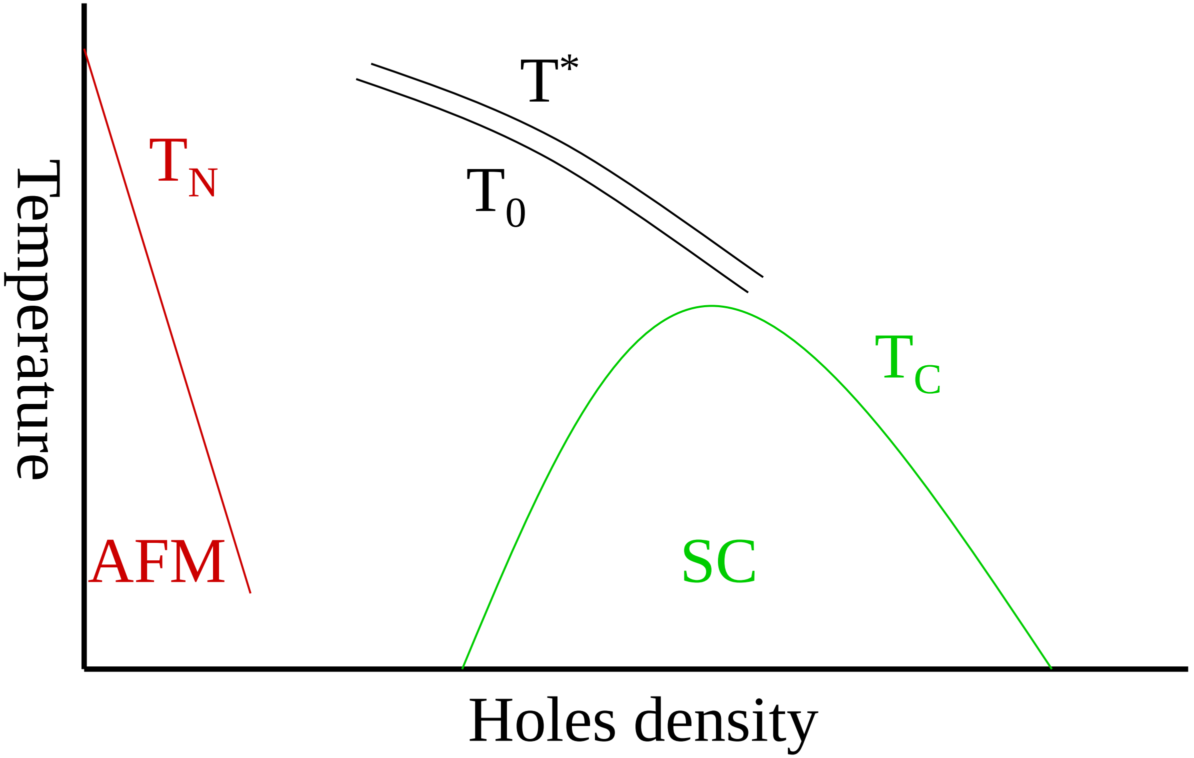
Phase diagram of the cuprates

- Above some doping level superconductivity emerges.
- At these doping levels, even the “normal” state is not normal.
- Superconductivity (SC) in these materials seems to be very different from SC in metallic superconductors.



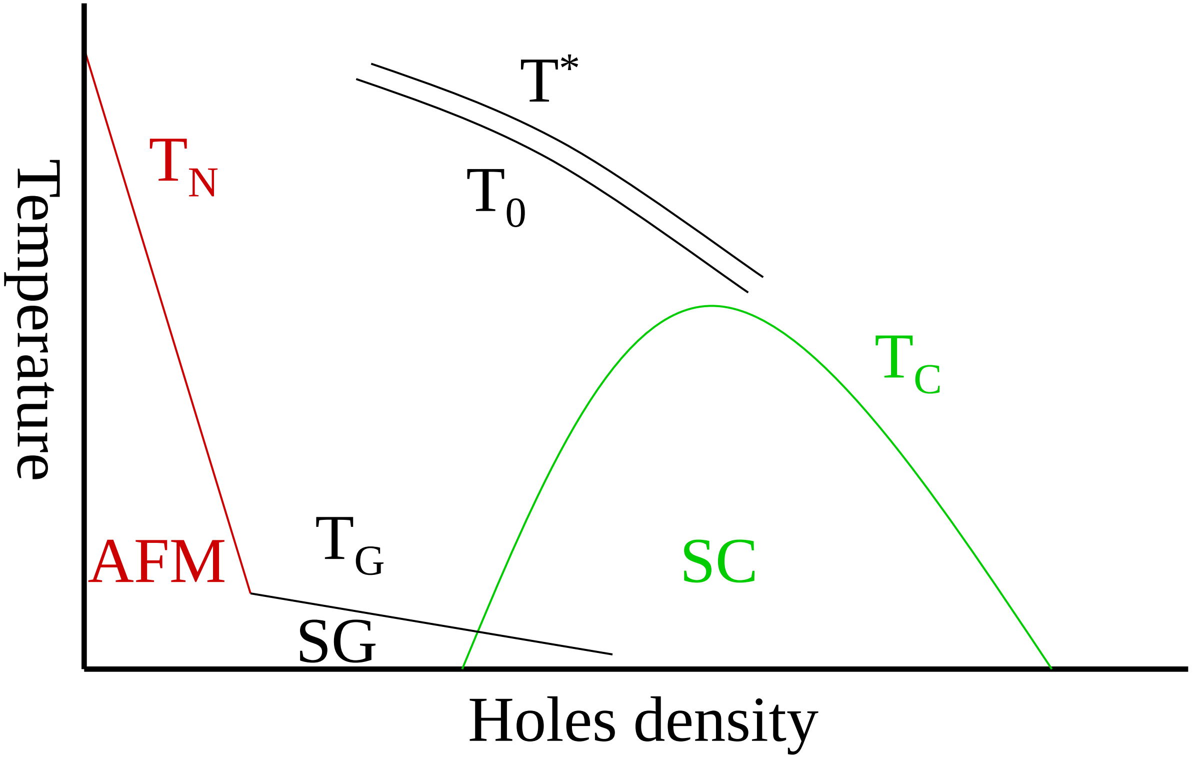
Normal state correlations

- Even above Tc the system is not a Fermi liquid (Pseudo gap).
- AFM excitations/correlations even at optimal doping (Spin gap).



Spin-Glass phase

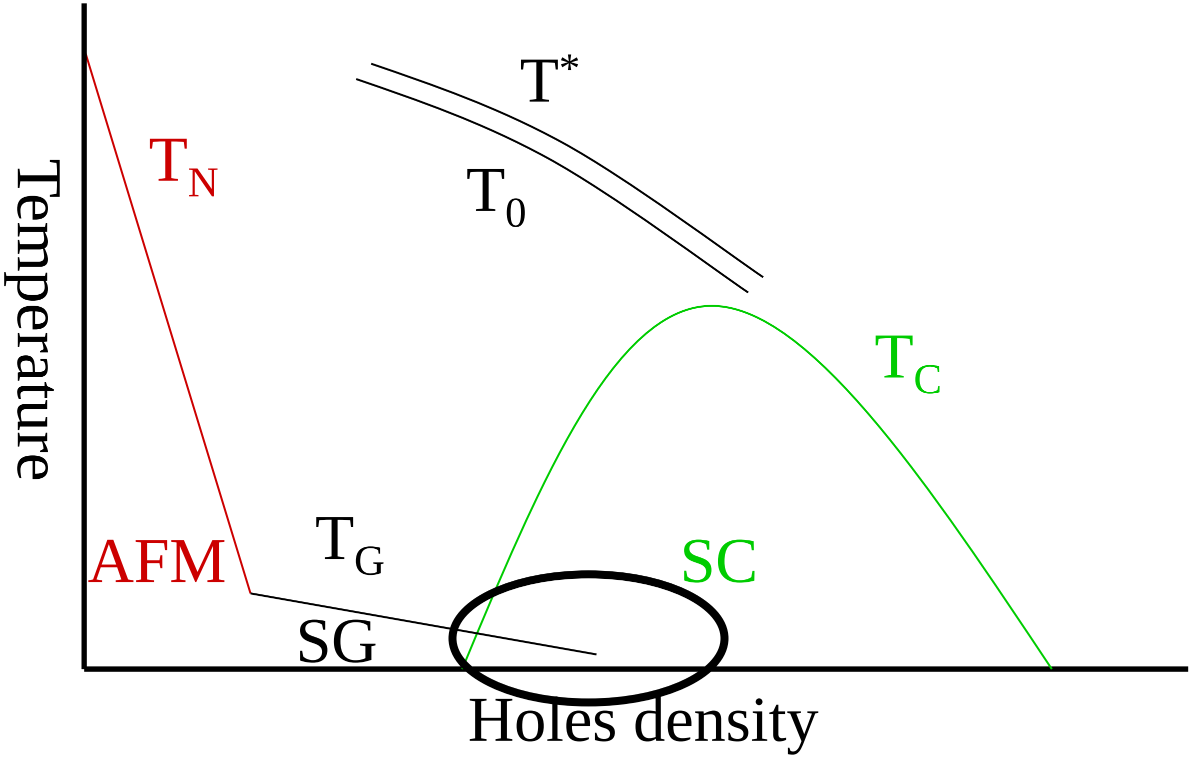
- At intermediate doping levels a spin-glass phase can be found.
- It was identified using NQR and μSR.



Motivation

•Despite the AFM Correlations there is **NO EXPERIMENTAL EVIDENCE** for a connection between AFM and superconductivity.

•The place to look for correlations between MAGNETISM and SUPERCONDUCTIVITY is the spin-glass phase.

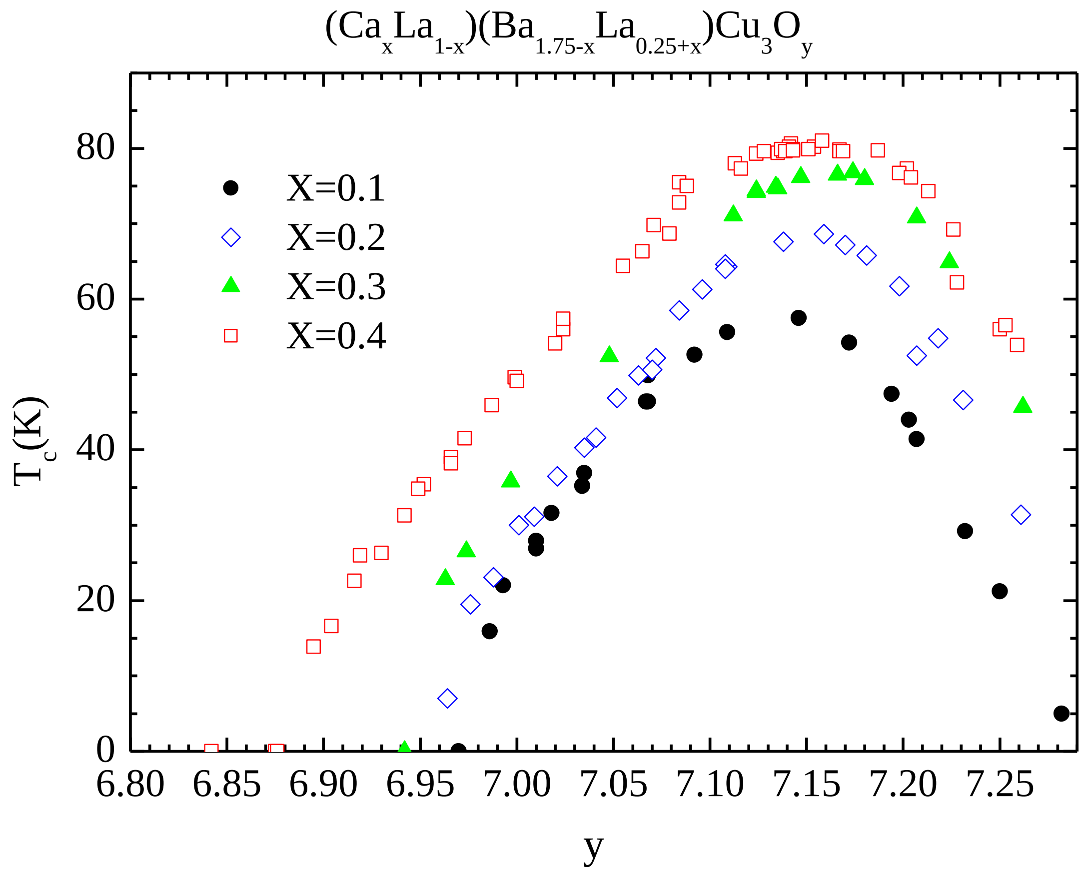


The CLBLCO system

$$(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$$

CLBLCO was chosen due to its characteristics:

- 123 structure
- Overdoping is possible.
- Doping is *x*-independent.



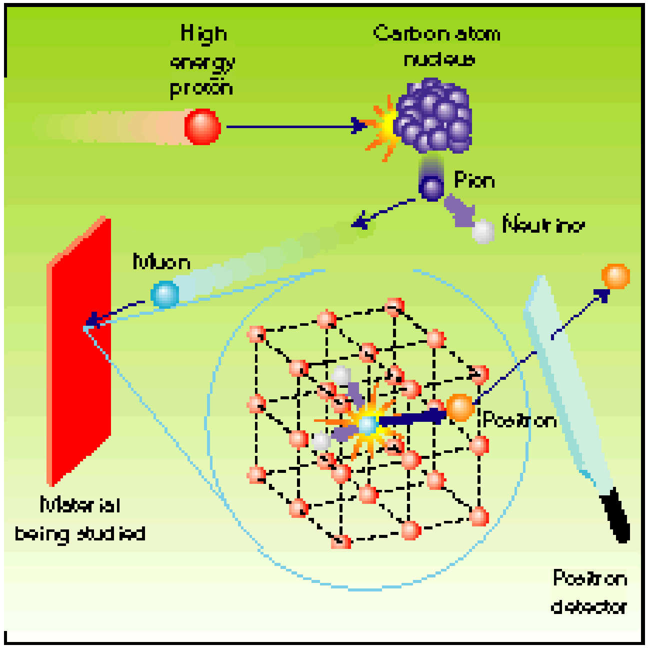
CLBLCO allows T_c (or doping) to be kept constant and other parameters to be varied, with minimal structural changes.

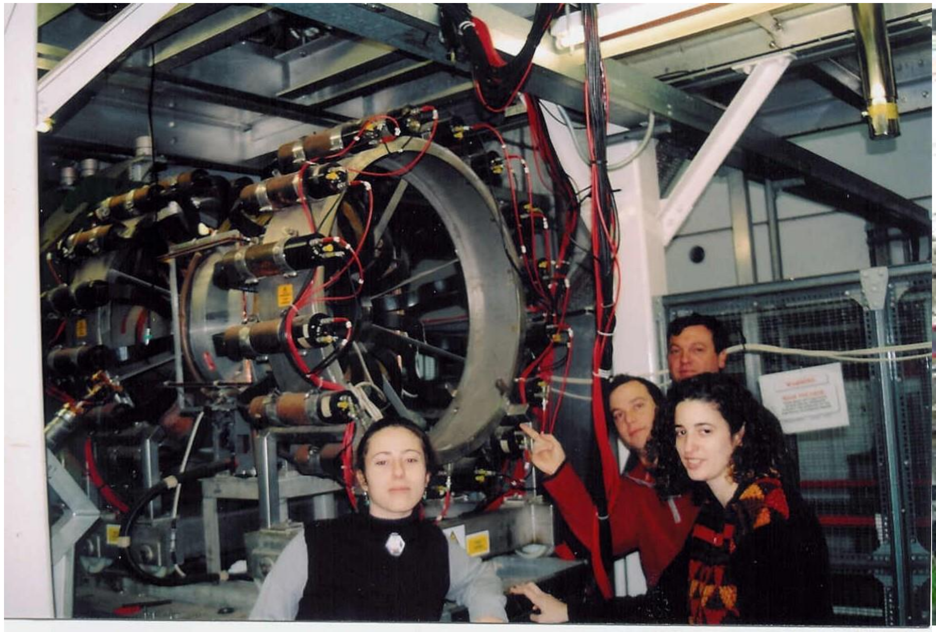
Work plan

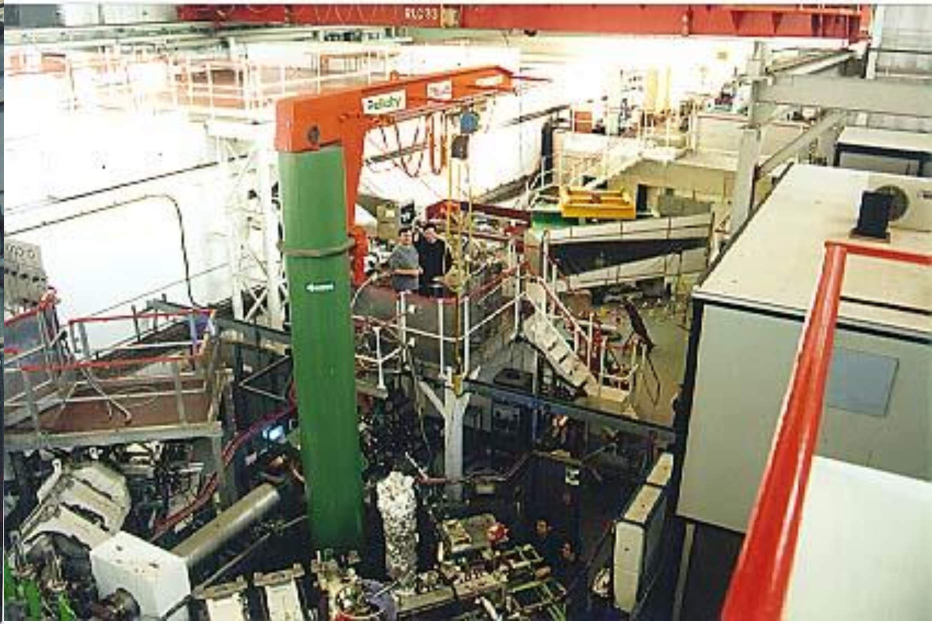
- We plan to measure T_g and T_c for many CLBLCO samples, with different x and y values.
- T_g , the spin-glass transition temperature, will be measured by μSR.
- We will look for correlations between these two transition temperatures.

Principles of μSR

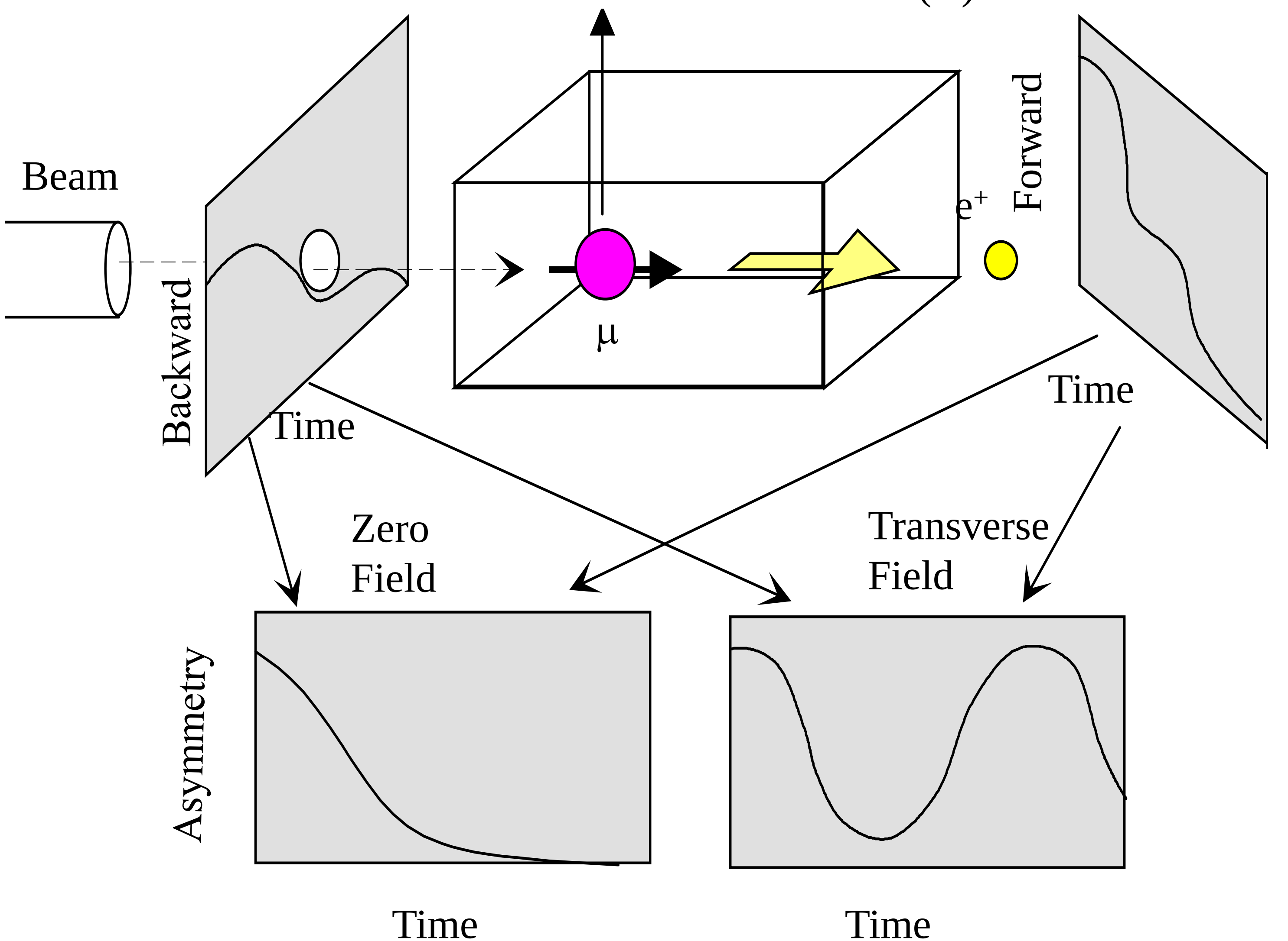
- 100% spin polarized muons.
- μ life time : 2.2μsec.
- Positron emitted in the spin direction.
- Very sensitive to internal magnetic fields: 0.1G – 1T







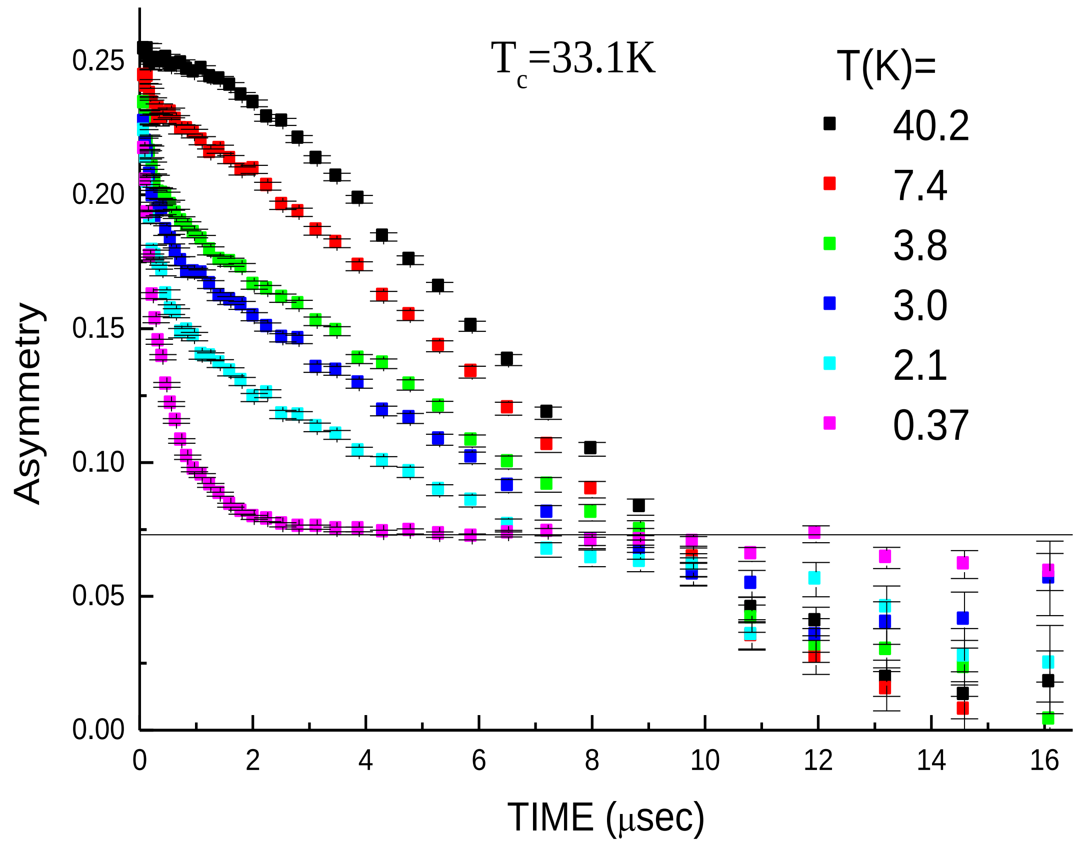
Principles of μSR



- Asymmetry = (F-B)$\propto P^{z}_{\mu}(t)$.

Raw ZF μSR data

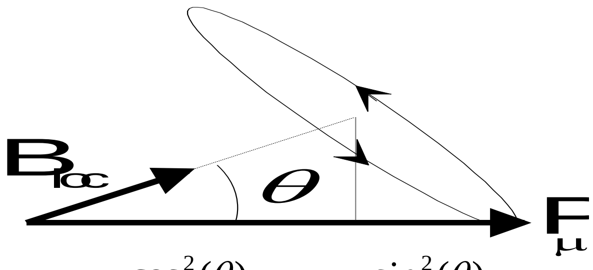
- High T $P_z(t)$ is from nuclei.
- Sudden change in $P(t)$ well below T_c.
- There are two contributions.
- One amplitude grows, the other decreases.
- There is recovery to 1/3.



- At base T, relaxation is over-dumped.

To understand this spin glass phase lets examine the base T data.

μSR in Zero Applied Field: Static Case

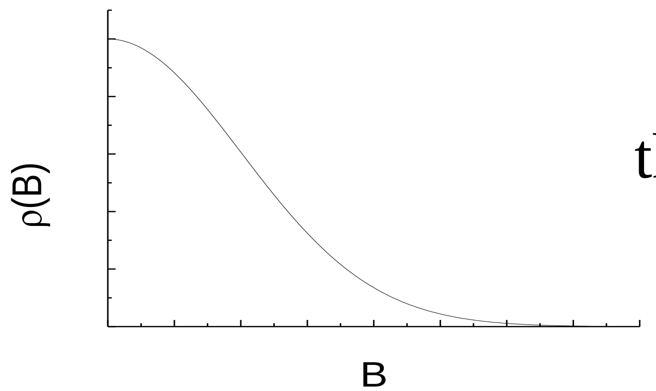


$$P_z(\mathbf{B},t) = \cos^2\theta + \sin^2\theta\cos(\gamma_\mu |B| t)$$

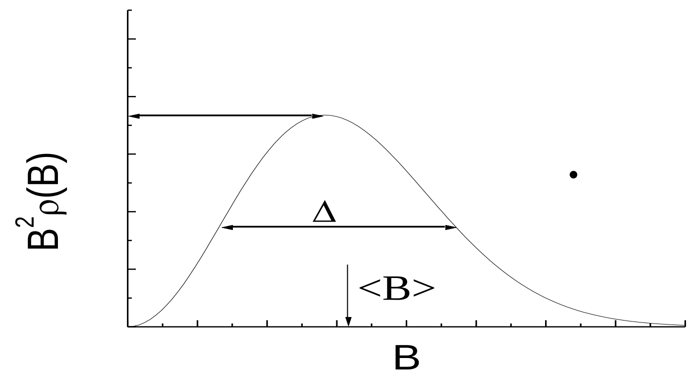
$$\cos\theta = \frac{B_z}{B}$$

On the average $P_z(t) = \frac{1}{3} + \frac{2}{3}\int B^2 \rho(|B|)\cos(\gamma_\mu |B| t)\, dB.$

If



then



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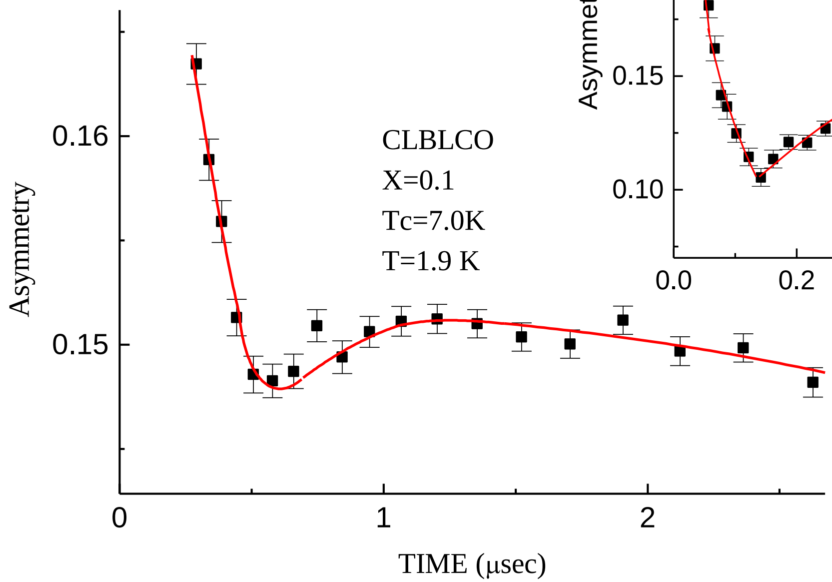
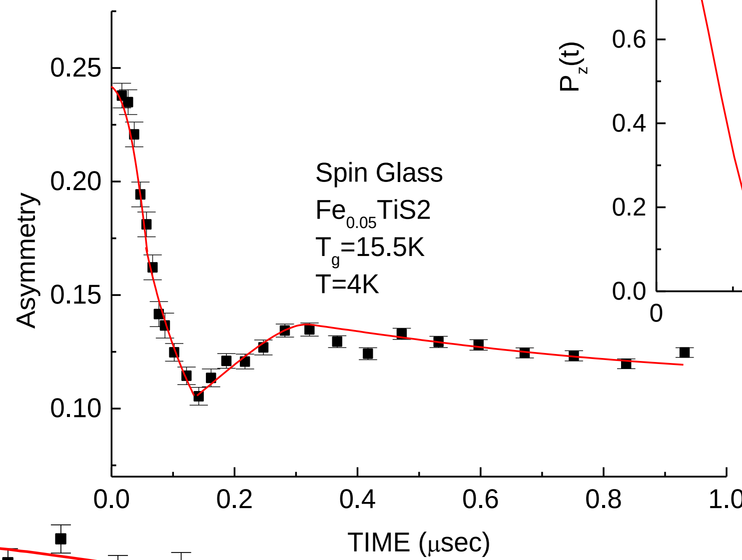
We expect dumped oscillations in $P_z(t)$.

We expect $\lim_{t\to\infty} P_z(t) = \frac{1}{3}.$

Demonstration

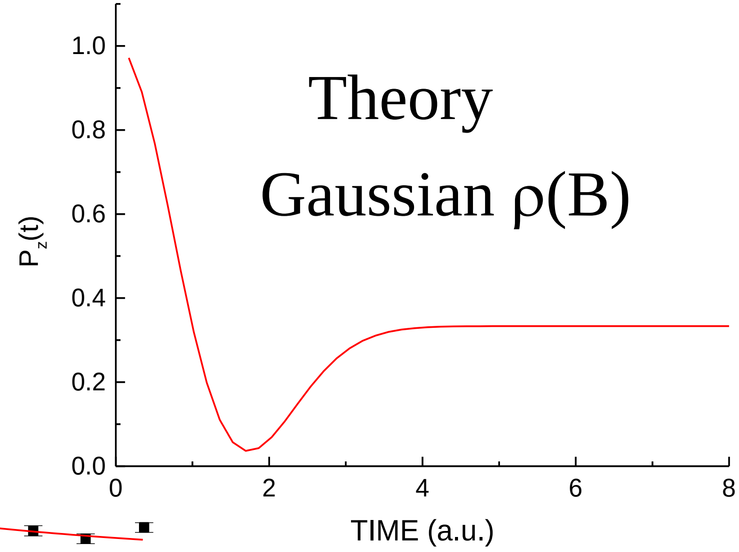
Experiments





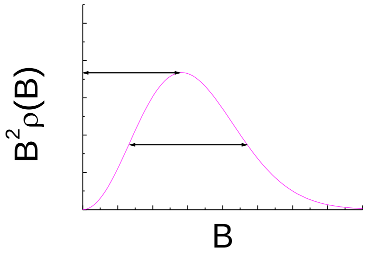
Theory

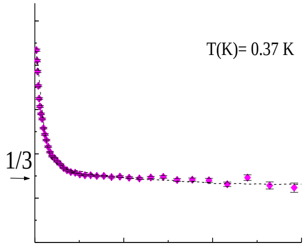
Gaussian ρ(B)



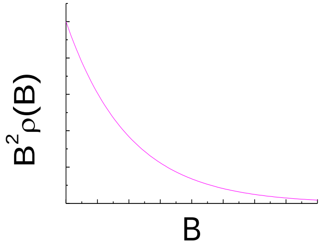
- The peek in $B^2\rho(B)$ corresponds to a dip in $P_z(t)$.
- The position of the dip is determined by the width of $\rho(B)$.
- The recovery of $P_Z(t)$ is to 1/3.

The case of CLBLCO

The situation 

is not possible in CLBLCO since 

(over dumped).

We must have 

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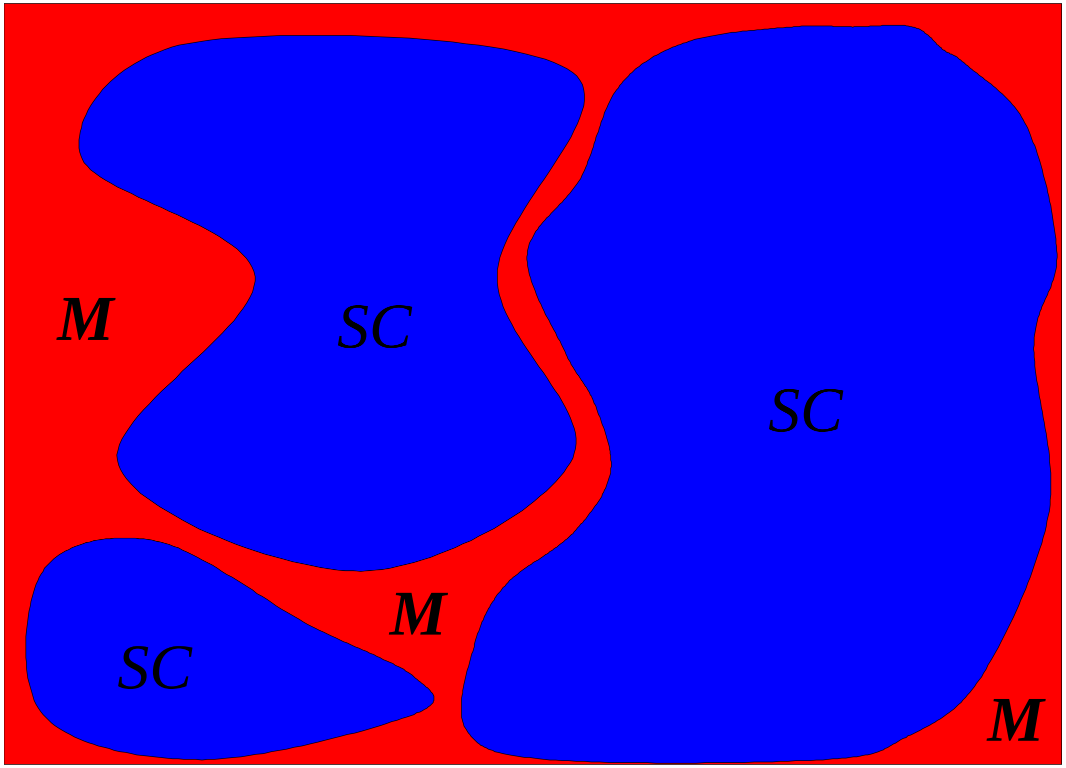
Namely, as $B \to 0$ we must have $\rho(B) \propto 1/B^2$.

There is an abnormal amount of sites with zero field.

Towards a model

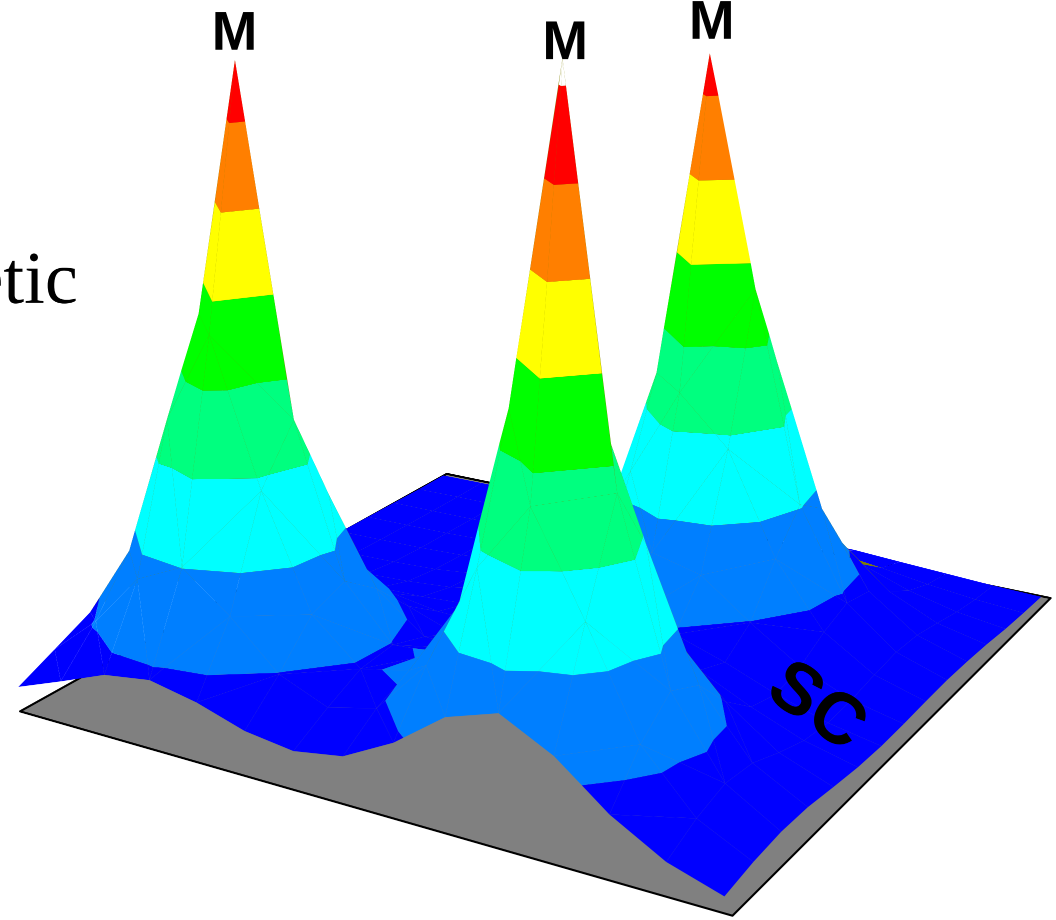


•If there was a macroscopic phase with zero field, it would be seen as an increase in the tail , to a value larger than 1/3.
•We can put an upper limit on size of such a phase.

A model

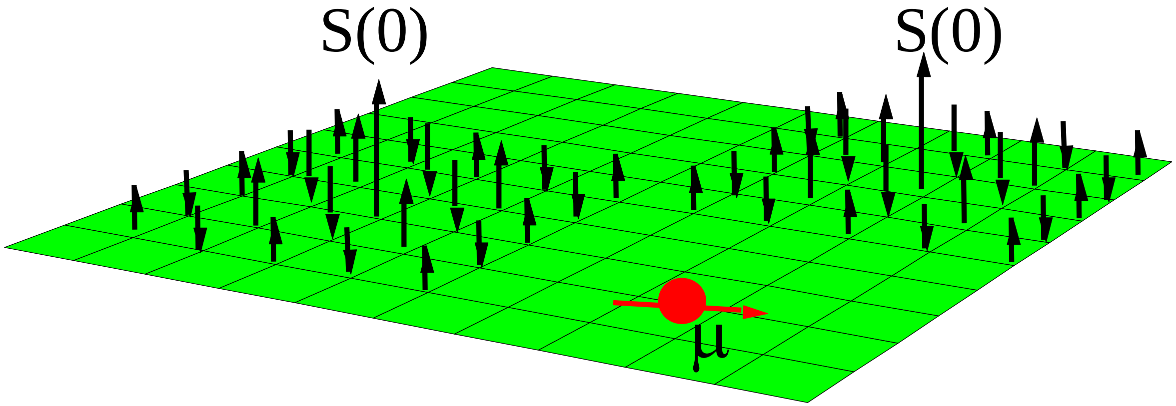
•The field from the magnetic phase penetrates into the superconducting regions.

• The staggered moments decay on a very short length scale.



Numerical Simulations

Muon polarization in a sample with random magnetic centers.



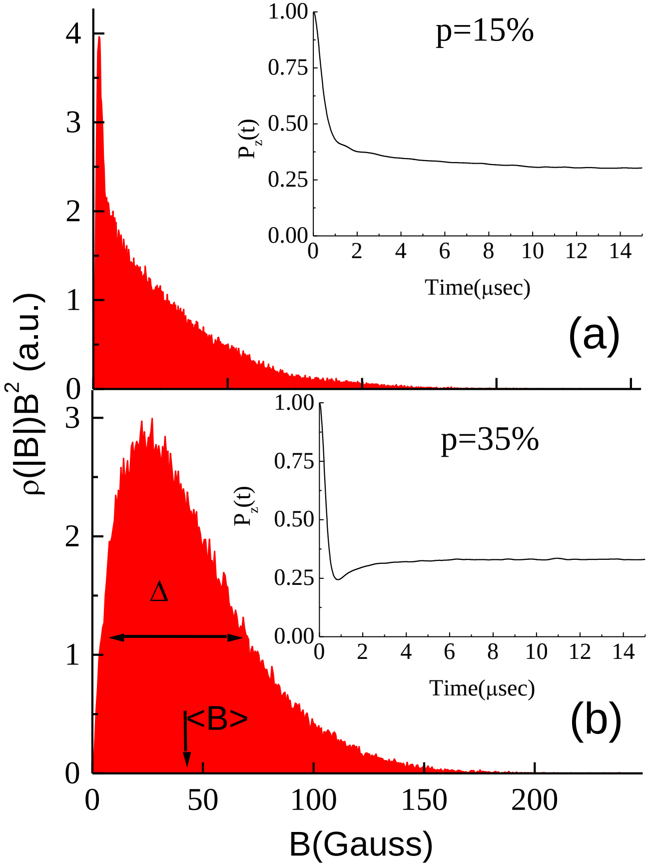
The position of **S**(0) is random.

$$\chi(\mathbf{r}) = (-1)^{\mathbf{r}/a} \exp(-r/\xi) \Rightarrow \mathbf{B}(\mathbf{r}).$$

Muon-electron spin interaction is dipolar.

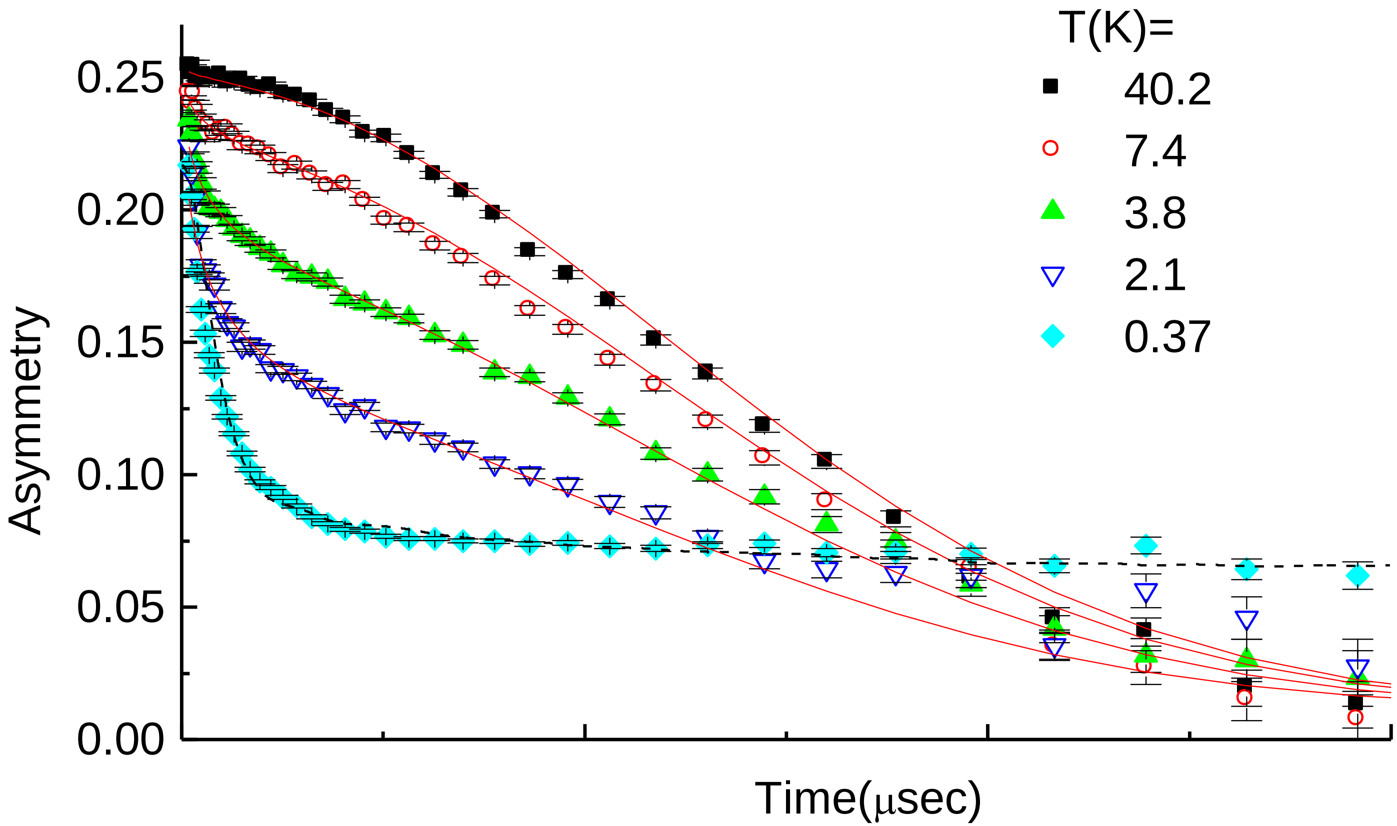
Simulation Results

p = magnetic concentration



Dumped oscillations at high *p*.
Over dumped oscillations at low *p*.

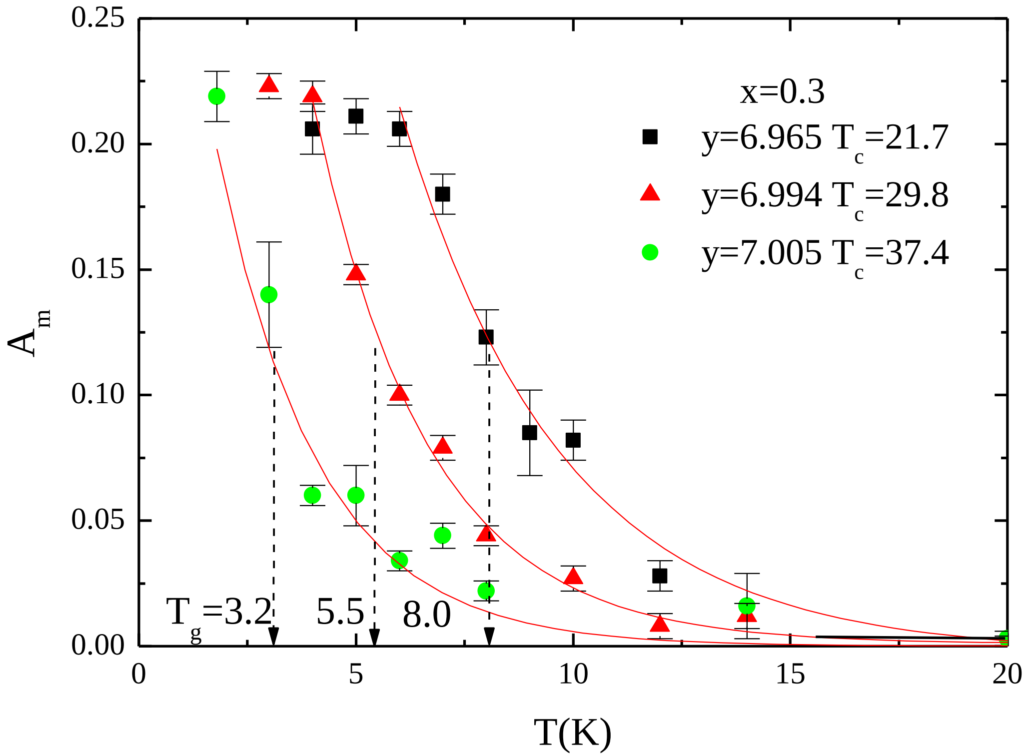
Raw ZF μSR data



We fit the data to $A(T,t) = A_m \exp(-\sqrt{\lambda t}) + A_n P(\infty,t)$.

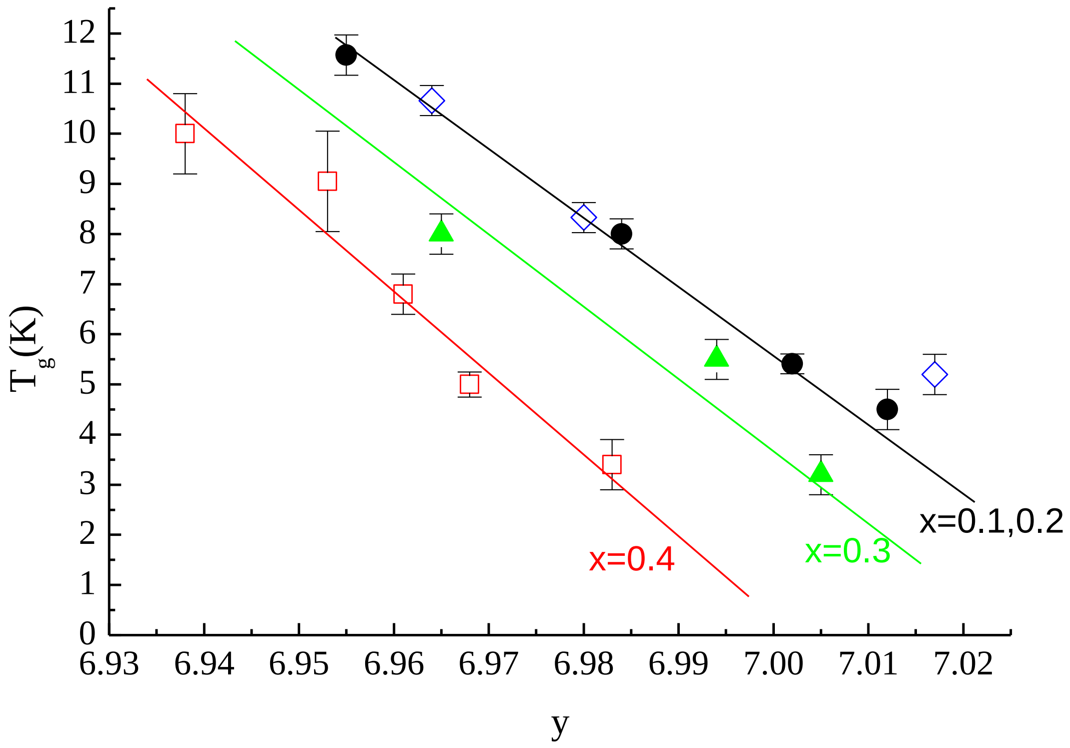
$P(\infty,t)$ is determined at high T.

Determination of T_g



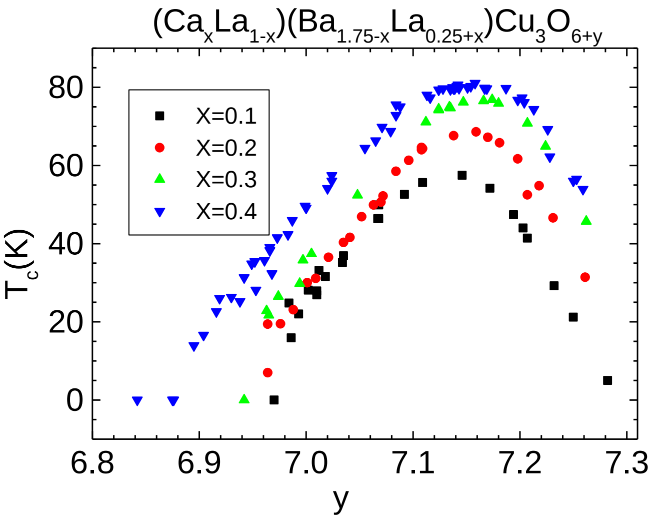
- At low *T* the magnetic amplitude saturates.
- The spin glass temperature T_g is the *T* where $A_m = A_m^{max}/2$.

T_g vs. x and y in $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$

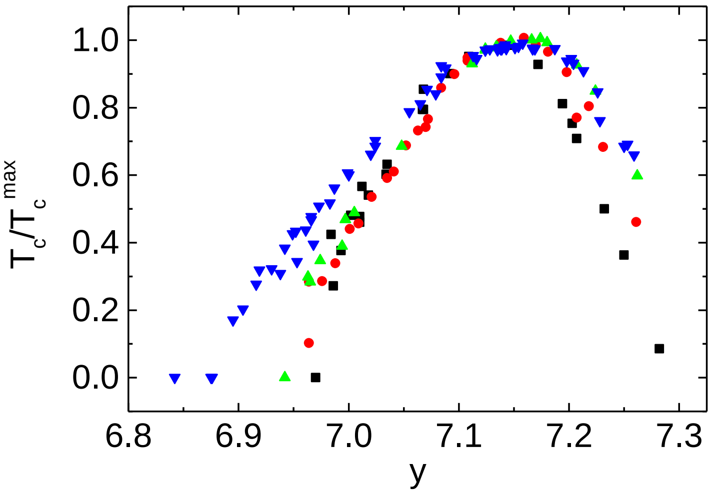


T_g decreases as doping increases.

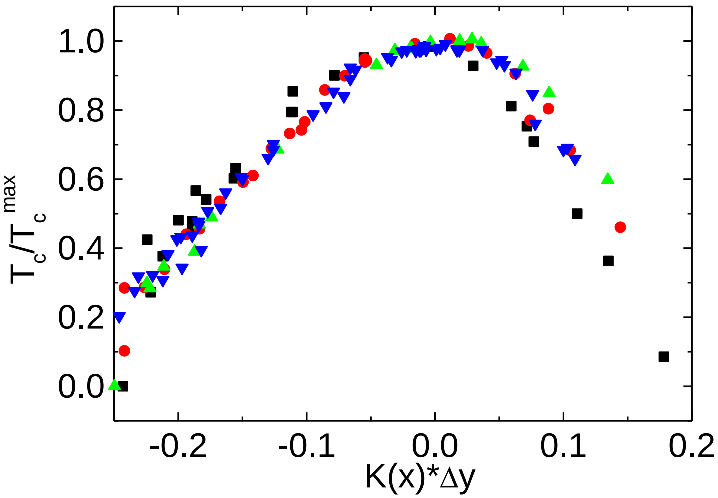
Scaling

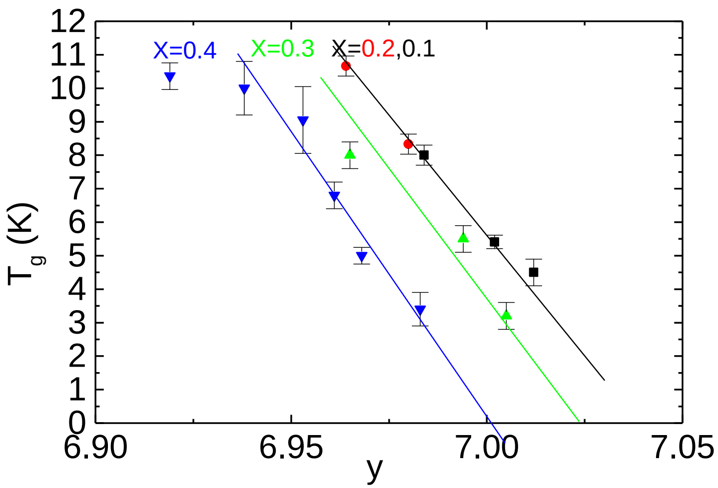


$T_C \rightarrow T_C / T_C^{max}$

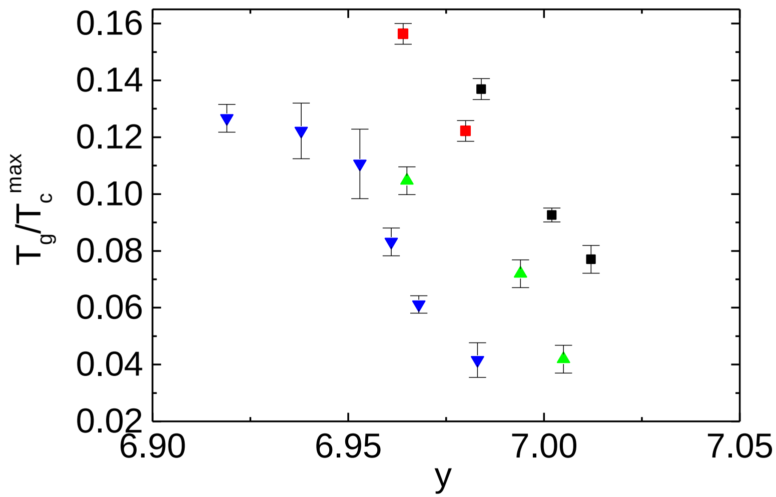


$y \rightarrow K(x)\Delta y$

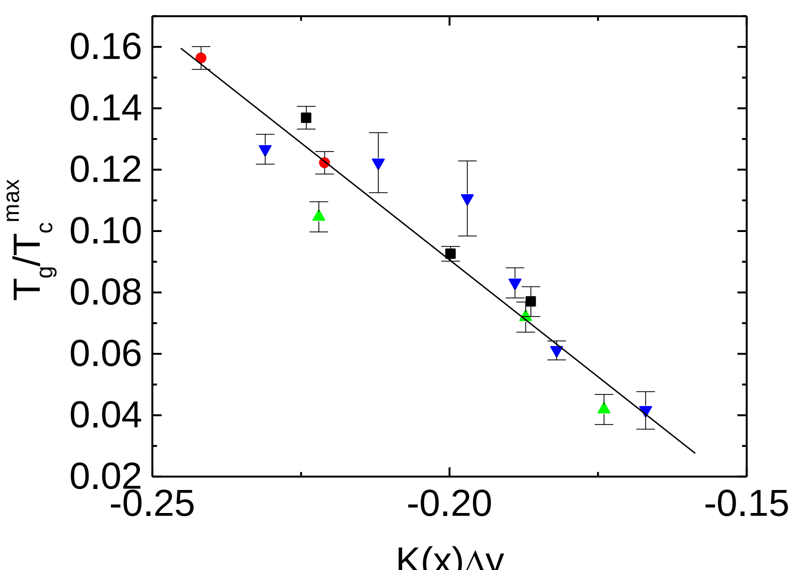




$$T_g \to T_g / T_C^{\max}$$



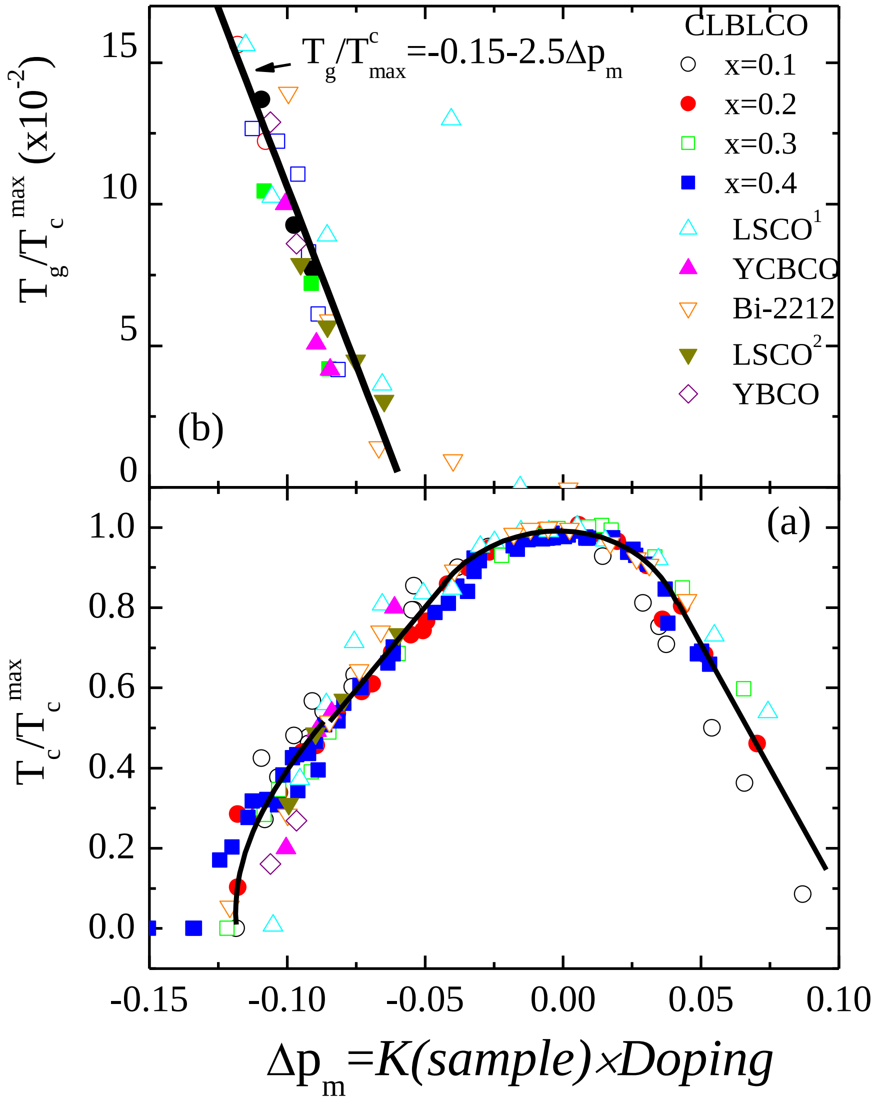
$$y \to K(x)\Delta y$$



Other compounds

For $La_{2-x}Sr_xCuO_4$

$$\Delta p_m = x - 0.16.$$



Data from:

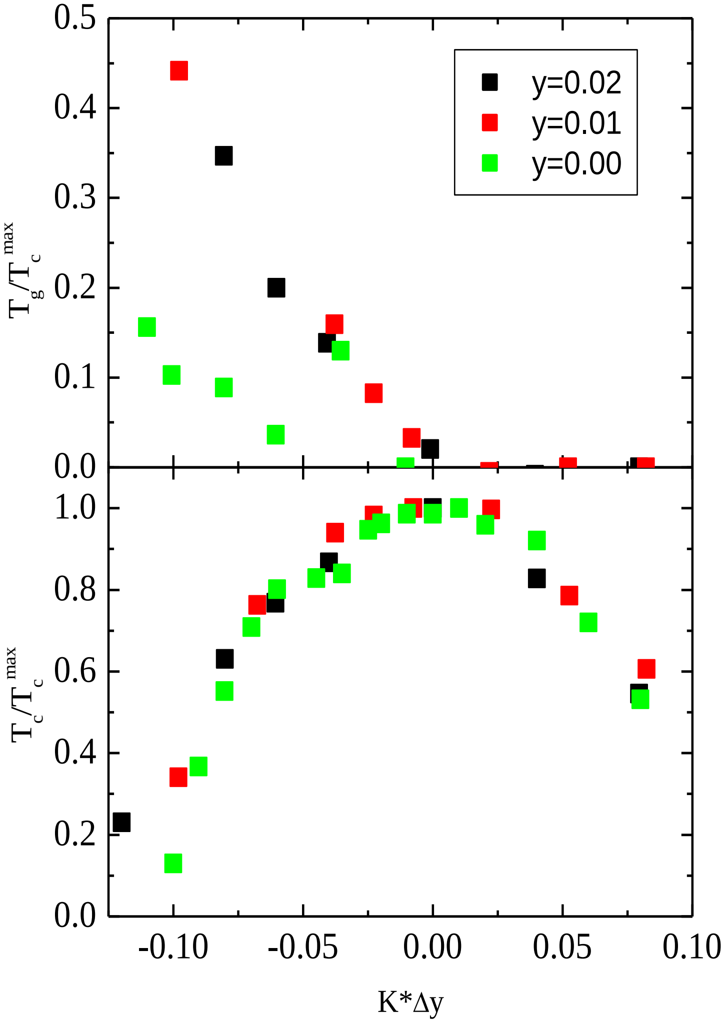
Niedermayer et. al. PRL ,80, 3843 (98).

Panagopoulos et. al. PRB, 66, 64501 (02).

Sanna, unpublished.

Zn doping

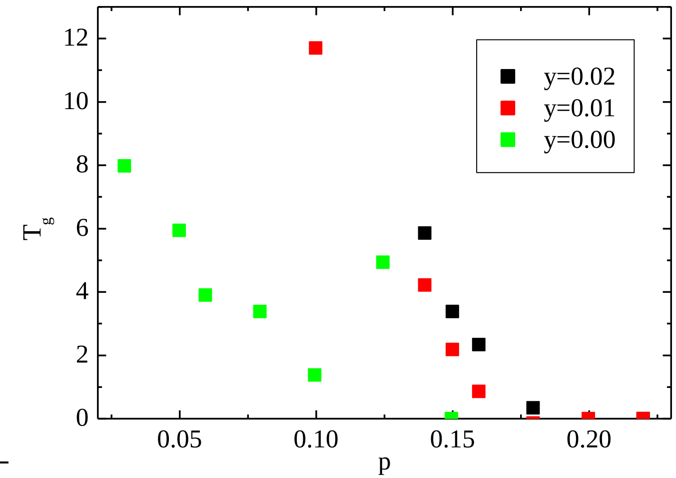
(Panagopoulos $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$)

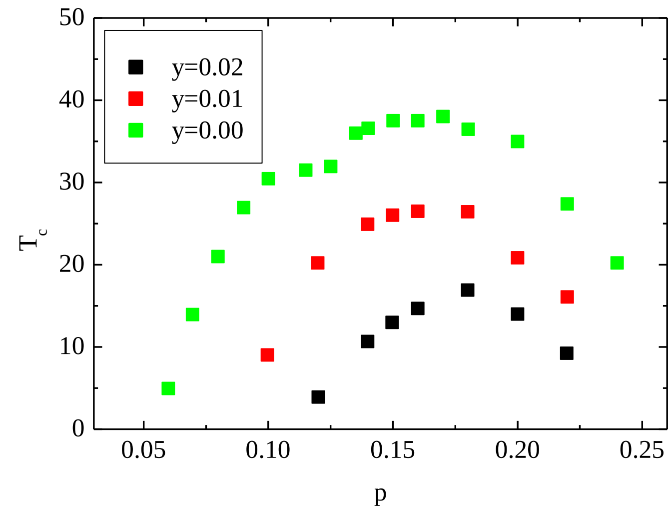


$T_c \Rightarrow T_c\,/\,T_c^{max}$

$T_g \Rightarrow T_g\,/\,T_c^{max}$

$y \Rightarrow K(x)\Delta y$





In this case the scaling transformation of T_c does not apply for T_g.

Single energy scale.

Before Scaling

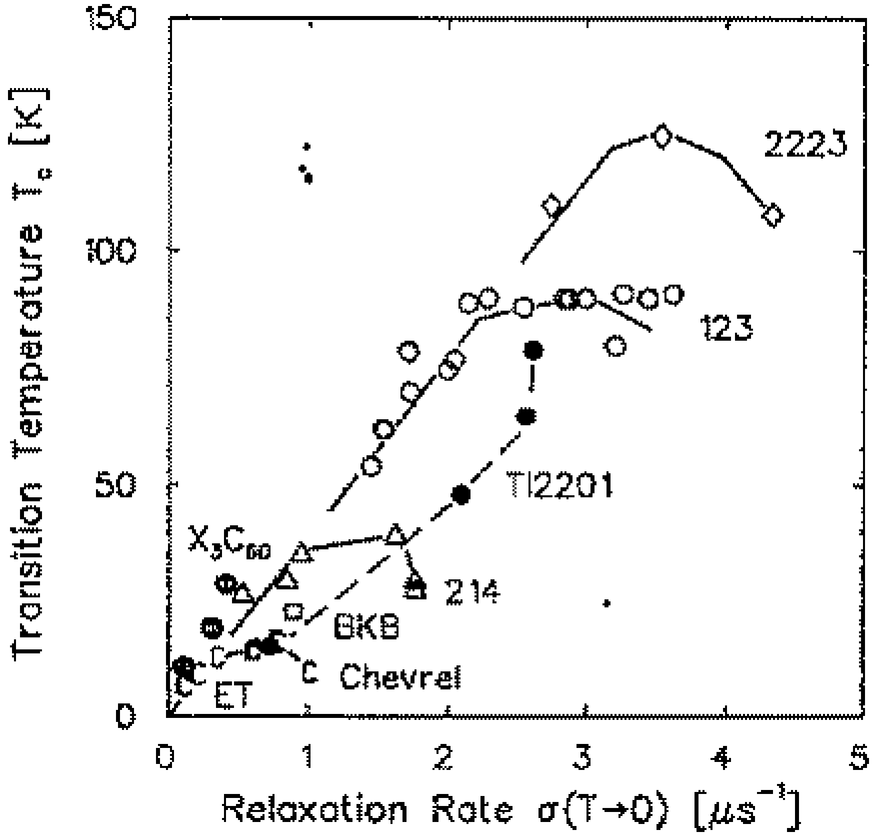
- The vertical axis represents energy.
- The horizontal axis represents density.

After Scaling

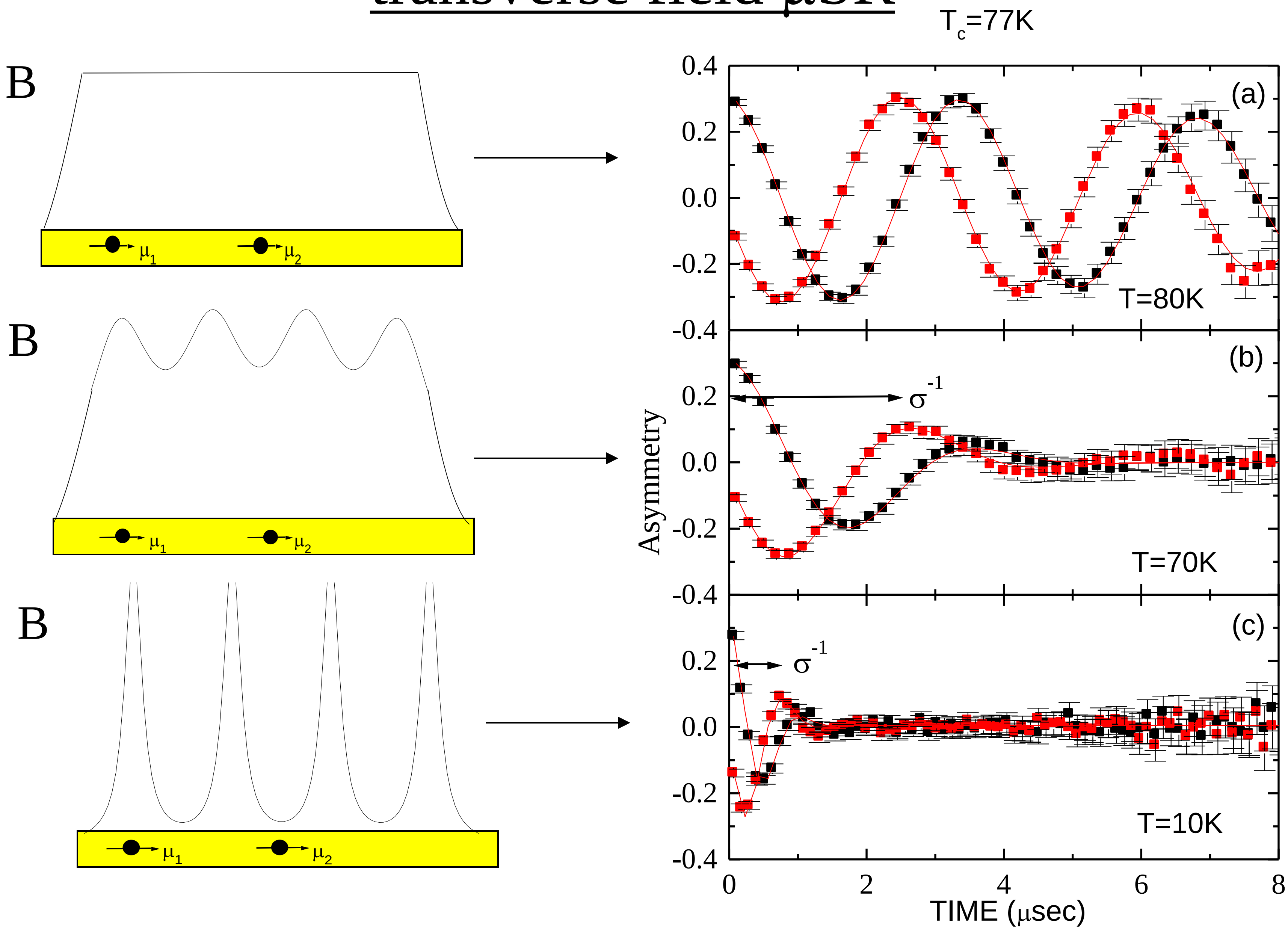
- The vertical axis is dimensionless.
- We scaled using a single energy scale, $T_C^{\max}$, both T_C and $T_{\dot{g}}$
- Both the Magnetism and the Superconductivity are governed by the same energy scale.

Additional background before interpretation

- The Uemura relation: $T_c = \alpha \frac{n_s}{m^*}$
- α is common to all HTSC.

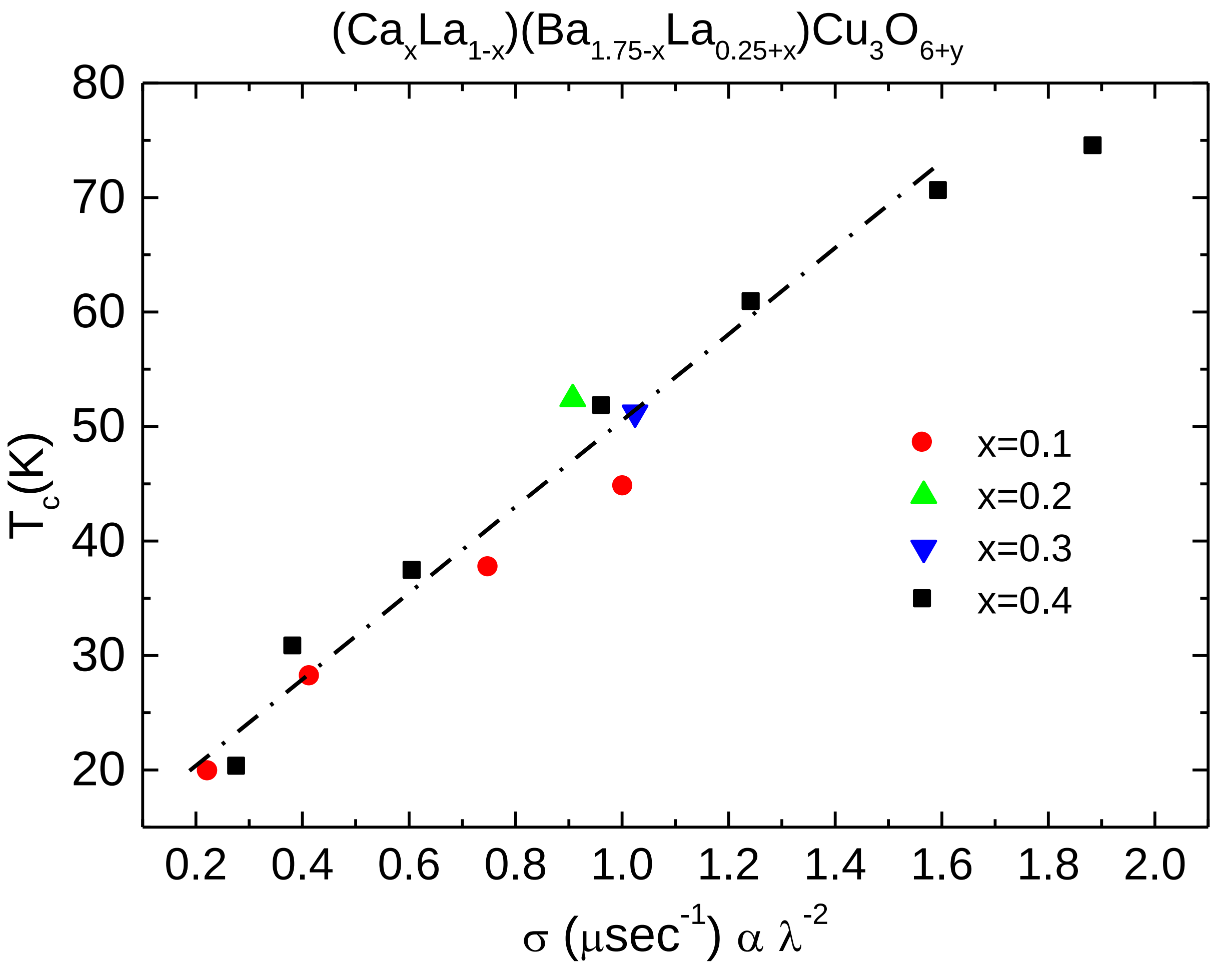


Penetration depth determination with transverse field μSR



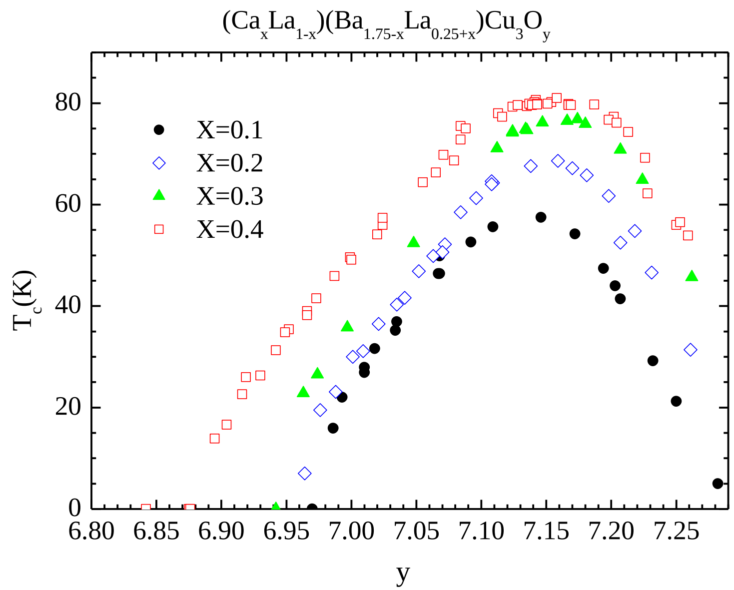
Uemura relations for the CLBLCO system

•We determine the muon relaxation rate which is proportional to λ^{-2}.



Equal T_c means also equal λ and equal n_s/m^*

- Using the London equation we know: $\lambda^{-2} \propto n_s$
- The results show that: $T_C \propto n_s$
- According to simple valence sums, the holes density in the CLBLCO system is independent of x (the Ca content).
- We can have samples with equal Tc, but different doping.



- Not all the doped holes contribute to the superfluid density!
- This is the origin of the scaling factor K.

Intermediate Conclusion

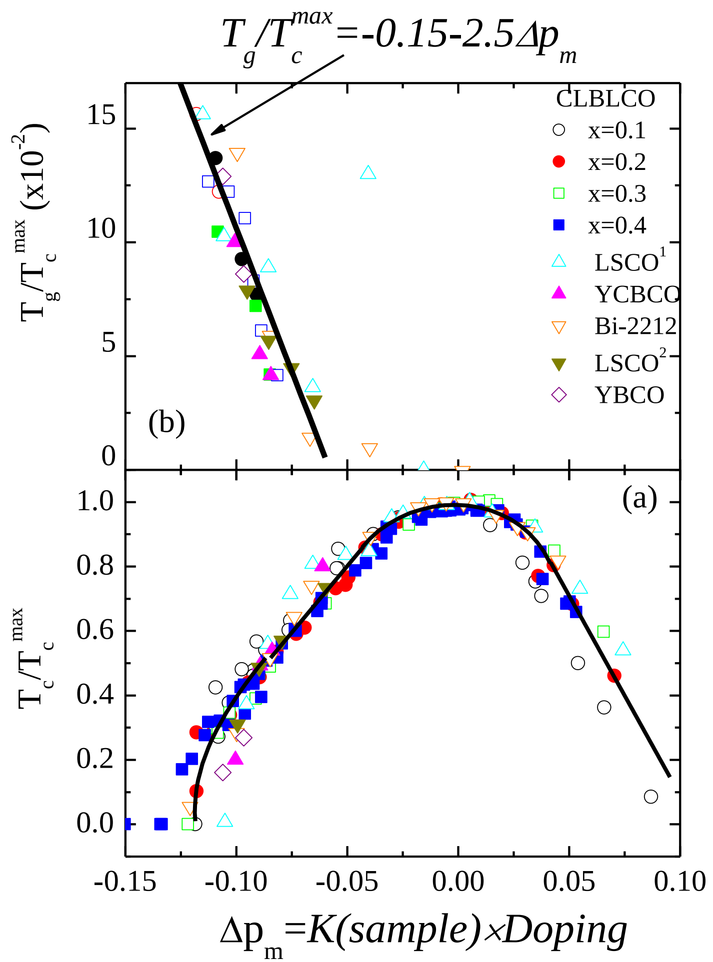
$$T_c = J_f \times n_s(\Delta p_m).$$

where J_f can vary between cuprates families.

Therefore, $T_c^{\max} = J_f n_s(0)$ and

$$T_g = J_f n_s(0)(-0.15 - 2.5\Delta p_m).$$

T_c and T_g have the same energy scale.



From experiment to theory

- We discuss models with both antifferomagnetic(AF) and superconducting (SC) phases.
- The Hubbard model at half filling (zero doping) will give us the Mott AF phase.
- Some believe superconductivity is also contained in this model.

$$H = -t \sum_{<ij>} (c_i^+ c_j + h.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

• Altman and Auerbach derived an effective Hamiltonian by solving the Hubbard model on 4 sites and keeping only low energy states.

• The effective model is a model of 4 interacting bosons.

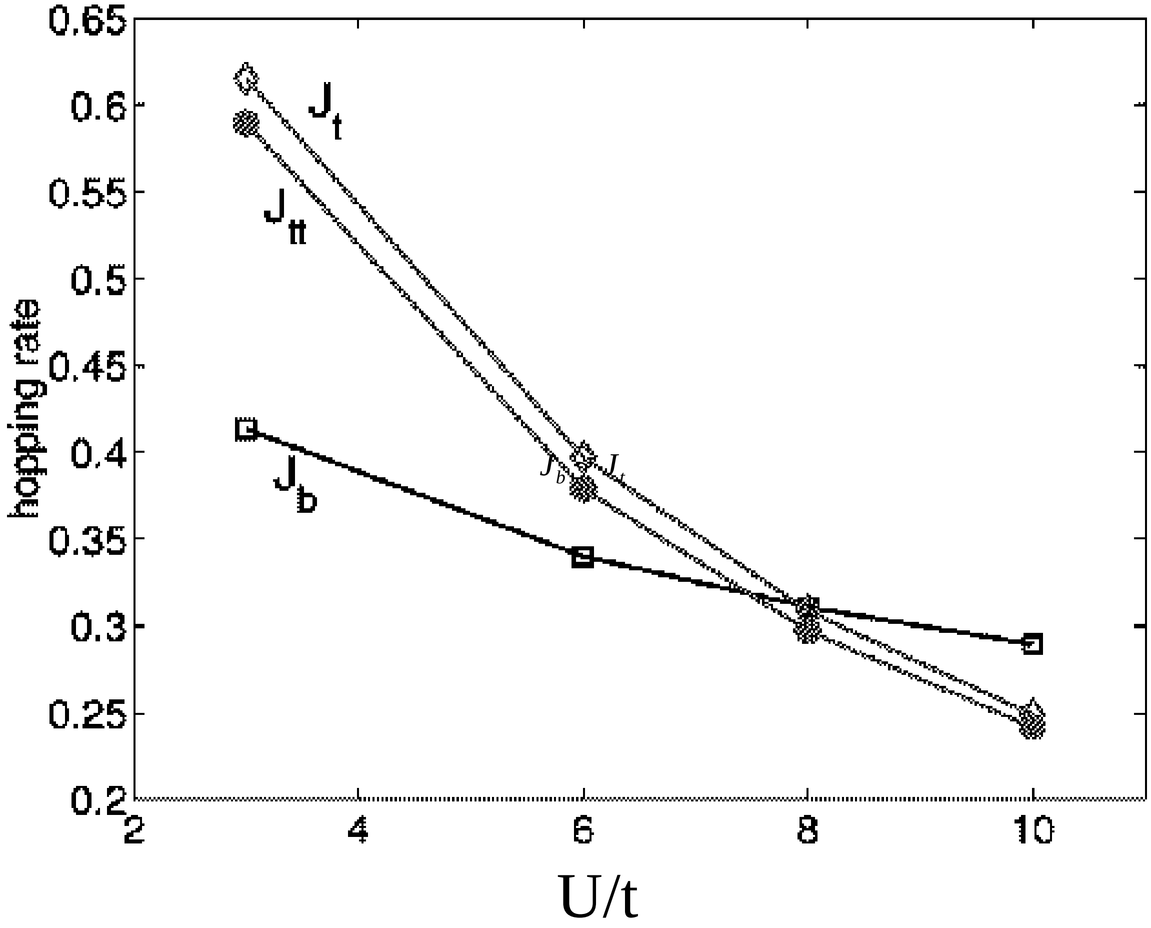
$t^+_{a,i}$ Is the creation operator of a magnon triplet on site i.

b^+_i Is the creation operator of an hole pair on site i.

$$H^b = (\varepsilon_b - 2\mu)\sum_i b_i^+ b_i - J_b \sum_{<ij>} (b_i^+ b_j + h.c.)$$

$$H^t = \varepsilon_t \sum_{i\alpha} t_{i\alpha}^+ t_{i\alpha} - J_t \sum_{\alpha <ij>} (t_{ia}^+ t_{j\alpha} + h.c)$$

Theoretical prediction



Different compounds can have different U and t.

In the range of parameters were pair binding is favorable

$$J_b \sim J_t$$

The model provides

AFM phase (condensate of t bosons at $\mu < \mu_c$)

SC phase (condensate of b bosons at $\mu > \mu_c$)

The Uemura relation $$T_c \propto J_b n$$

And the relation $$J_t \sim J_b$$

- In the AFM phase T_N is governed by J_t .
- We make a nontrivial assumption that, although the lattice is doped:

$$T_g \propto J_t$$

$$T_c = J_b n_s$$

$$T_g = J_t f(\Delta p)$$

$$\Rightarrow$$

$$\frac{T_c}{T_c^{\max}} = \frac{n_s(\Delta p)}{n_s(0)}$$

$$\frac{T_g}{T_c^{\max}} = \frac{J_t}{J_b} \frac{f(\Delta p)}{n_s(0)}$$

Therefore, according to our data J_b is proportional to J_t .

This is only slightly different from the AA prediction.

Summery

•We found that at intermediate doping levels, there is a microscopic phase separation in CLBLCO samples.

•We found a scaling relation between T_c and T_g.

•This scaling relation is found to be common to many HTSC families.

•The scaling relation agrees with theoretical predictions.

Acknowledgements

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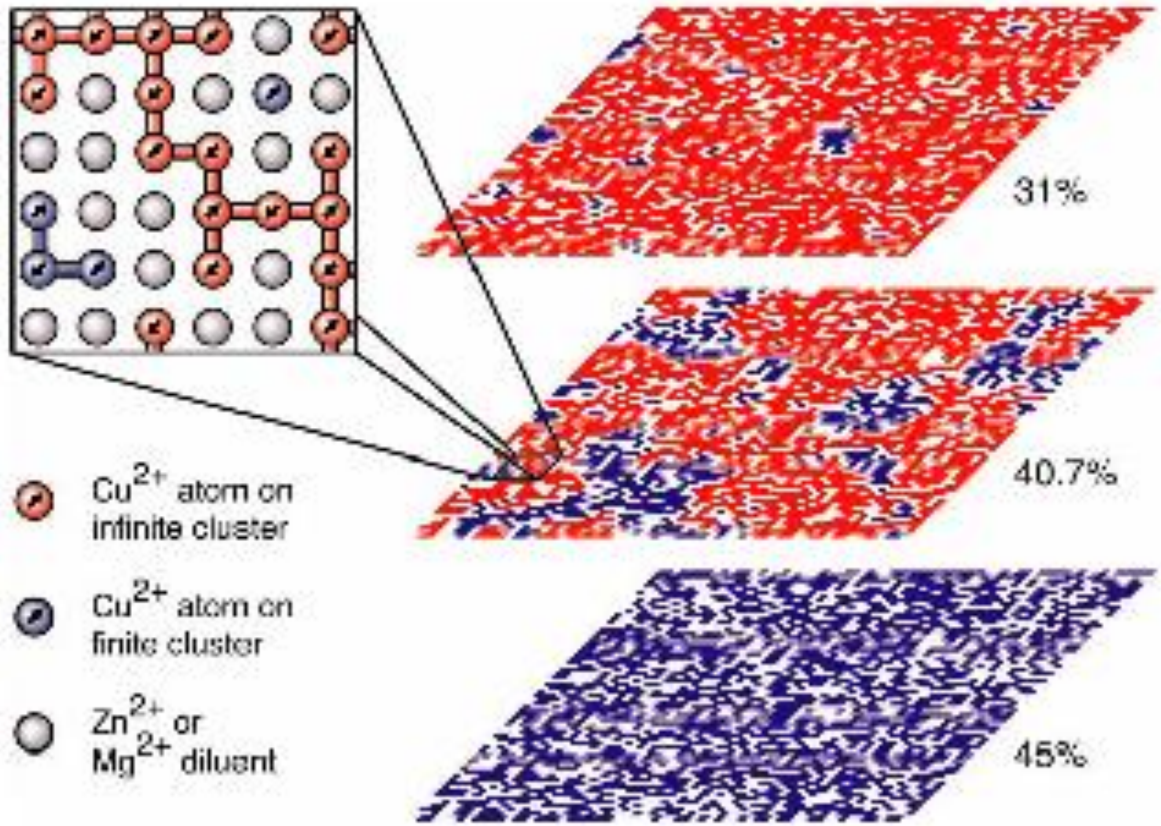

- Works on diluted AFM showed that the long range AF order survives up to a dilution level of 40%.

- T_N decreases monotonically as the dilution is increased.